

**Fine-Resolution Imaging of Solar Features  
Using Phase-Diverse Speckle:  
Annual Status Report**

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In this second (and final) annual status report for NASA Grant Number NAGW-4069, we review the background for the research, describe the accomplishments of the second year of this two-year grant, list the presentations and publications delivered under this grant, and provide a brief description of the research planned for the future.

## **1. Background**

Recall that *Phase-Diverse Speckle* (PDS) is a novel imaging technique intended to overcome the degrading effects of atmospheric turbulence on fine-resolution imaging. As its name suggests, PDS is a blend of phase-diversity and speckle-imaging concepts. A PDS data set consists of a short-exposure image pair, one conventional (in focus) and one intentionally defocused (introducing phase diversity), for each of several atmospheric realizations. We use maximum-likelihood estimation to jointly estimate the object (common to all images) and a phase-aberration function for each atmospheric realization. Our goal under this grant has been to develop PDS for use in ground-based solar observing. The method is appealing because the optical hardware is simple and provides an alternative to adaptive optics, there is no need for a speckle-calibration step (which is needed for conventional speckle imaging but is problematic in solar observations), significantly fewer short-exposure images are required relative to conventional speckle imaging (suggesting use in time-series reconstructions), fixed telescope aberrations are accommodated and can even be estimated, and the method can be generalized to accommodate anisoplanatic effects.

## **2. Second-Year Accomplishments**

Recall that in the first year of funding, we were able to achieve a major milestone by successfully performing the first ever phase-diverse speckle reconstructions on real solar data. These reconstructions achieve very nearly diffraction-limited resolution. It is natural to ask if the fine-resolution detail recovered by PDS can be trusted. In the second year of funding we were able to validate the reconstructions. In addition we continued to develop our algorithms by investigating different wavefront parameterizations, by comparing our techniques with those of our collaborators from the Stockholm Observatory, and by expanding our capabilities to include time-series reconstructions.

Validation of reconstructions is an important milestone that was reached in the second year. Validation occurred by simulation investigation, by demonstrating internal consistency of PDS estimates, and by comparing PDS reconstructions with those produced from well accepted speckle-imaging processing. We used simulations to accurately model the data collected by M. Löfdahl and G. Scharmer of the Stockholm Observatory with the Swedish Vacuum Solar Telescope (SVST). Several sources of error were simulated: CCD noise, quantization error, image misalignment, and defocus error. In addition to these error sources, a

mismatch between the atmospheric turbulence model used during image restoration and the real turbulence was introduced. For the true object we used a simulated solar granulation object derived from a 3-D physical model of the photosphere (courtesy of Dr. Robert Stein, Michigan State U.). These simulations demonstrate that fine-resolution information can be reliably recovered out to at least 70% of the diffraction limit without significant introduction of image artifacts. Additional confidence in the SVST restoration is obtained by comparing its spatial power spectrum with previously-published power spectra derived from both space-based images and earth-based images corrected with traditional speckle-imaging techniques. We find that the shape of the spectrum matches well with these previous measurements. In addition, C.U. Keller (NSO), an unpaid collaborator on this effort, processed 100 conventional images (a subset of the PDS data set) with accepted speckle-imaging techniques for comparison. We find our imagery to be consistent with, but slightly sharper than, the speckle-reconstructed imagery.

On June 22, 1995, PDS data were collected by R.G. Paxman, J.H. Seldin, G.H. Elste (U. Michigan), and C.U. Keller at the 76 cm Vacuum Tower Telescope at the National Solar Observatory (Sacramento Peak, NM). Three CCD cameras of the Zürich Imaging Stokes Polarimeter I were used in parallel. One camera was in focus, another was out of focus, and a third was behind a narrow-band tunable filter. PDS processing was used to remove the aberrations of the atmosphere and the telescope by using the simultaneous in-focus and out-of-focus images in a 5 nm passband around 656 nm. The point-spread functions determined in this relatively broad channel can then be used to restore the 0.05 nm bandpass images. In addition, a time-series restoration of a plage was performed that shows the highly dynamic photosphere at scales below 0.3 arcsec. The very fine spatial resolution combined with the good time resolution opens a new observational window to the study of the dynamics of the solar photosphere from ground-based observatories. The movie has been made available on the World Wide Web at

[http://www.erim.org/algs/PD/pd\\_home.html](http://www.erim.org/algs/PD/pd_home.html)

### 3. Presentations and Publications

In the second year of funding one refereed journal article was submitted, and three conference presentations (one with proceedings) were delivered. For completeness, we list in chronological order all publications and presentations produced under this two-year grant.

1. "Phase-diverse speckle reconstruction of solar data," J.H. Seldin and R.G. Paxman, in *Image Reconstruction and Restoration*, Proc. SPIE **2302-19**, San Diego, CA, July 1994 (recipient of *Best Paper Award*).
2. "Parameter dimension of turbulence-induced phase errors and its effects on estimation in phase diversity," B.J. Thelen and R.G. Paxman, in *Image Applications and Restoration*, Proc. SPIE **2302-23**, San Diego, CA, July 1994.
3. "Post-detection correction of turbulence-induced space-variant blur by using phase diversity," R.G. Paxman, B.J. Thelen, and J.H. Seldin, presented at the Annual Meeting of the Optical Society of America, Dallas, TX, October 1994.

4. "Simulation validation of phase-diverse speckle imaging," R.G. Paxman and J.H. Seldin, in *Signal Recovery and Synthesis*, 1995 Technical Digest Series **11**, 85-87 (Optical Society of America, Washington DC, 1989), Salt Lake City, UT, March 12-17 1995.
5. "Fine-Resolution Imaging of Solar Features Using Phase-Diverse Speckle," R.G. Paxman, J.H. Seldin, and G.H. Elste, presented at the 26th Meeting of the Solar Physics Division of the American Astronomical Society, Memphis, TN, June 4-8, 1995.
6. "Solar Granulation Restoration using Phase-Diverse Speckle Imaging: Verification via Simulation and Measurements," J.H. Seldin, R.G. Paxman, and G.H. Elste, presented at the 26th Meeting of the Solar Physics Division of the American Astronomical Society, Memphis, TN, June 4-8, 1995.
7. "Evaluation of phase-diversity techniques for solar-image restoration," R.G. Paxman, J.H. Seldin, M.G. Löfdahl, G.B. Scharmer, and C.U. Keller, *Astrophysical Journal*, submitted December, 1995.

#### **4. Future Research**

We have submitted a grant proposal entitled "Fine-Resolution Imaging of Solar Phenomena using Phase-Diverse Speckle," in response to the NASA research announcement Space Physics Supporting Research and Technology (NRA 95-OSS-11). The ultimate scientific motivation for the proposed 3-year effort is the improved observation of small-scale solar phenomena, including the temporal evolution of brightness features (granulation, facular points, penumbral filaments, umbral dots, and micropores) and their relation to evolving magnetic fields. To this end, the research plan is designed to accomplish three objectives: (1) Deliver phase-diverse speckle operational methodology and software to the solar astronomy community for widespread use; (2) Adapt phase-diverse speckle to improve other observational modalities, including time-series, narrow-band, polarimetric, Doppler, and spectroscopic observations; and (3) Demonstrate scientific observations with each of these enhanced observing modalities. Having shown the value of PDS in demonstration observations, we wish to help transition the technique into a tool for routine use by solar astronomers. Accordingly, we intend to refine the operational methodology and convert our research code into a user software package that can be used in the solar-astronomy community at large. In addition, PDS time-series reconstruction techniques will be refined and exercised to observe dynamic phenomena at spatial and temporal resolution unavailable from any other imaging modality. Finally, although PDS has been demonstrated for broad-band images, most scientific observations of interest will ultimately require narrow-band, spectroscopic, or polarimetric data. It is very important to generalize PDS to accommodate these data sets. We believe that the continued development of PDS observational technology will ultimately provide solar astronomers with a suite of inexpensive ground-based observational tools that can be routinely used to acquire near diffraction-limited images and time-series reconstructions.